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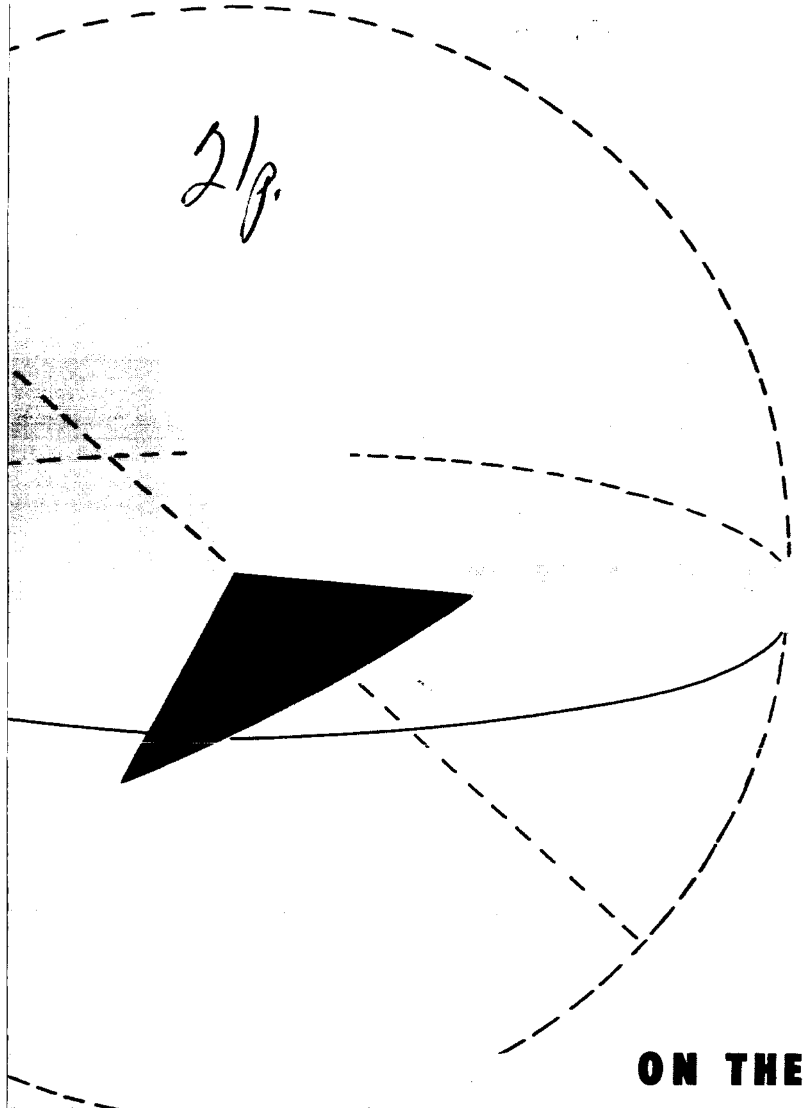

ON THE PRESENCE OF OXYGEN IN THE ATMOSPHERE OF VENUS

TRANSLATION NO. 33

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JET PROPULSION LABORATORY

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ON THE PRESENCE OF OXYGEN IN THE ATMOSPHERE OF VENUS[1]

V. K. Prokofyev, N. N. Petrova

I. INTRODUCTION

Spectra of reflected solar light from Venus in the region of the telluric oxygen α-band at a dispersion of 1 Å/mm were obtained with an echelle-spectrograph (grating spectrograph) attached to the solar tower telescope. The photometric reduction of the plates showed an asymmetry in the lines of the telluric oxygen α-band. This asymmetry can be due to a faint oxygen absorption band formed in the region above the cloud layer of the atmosphere of Venus.

Repeated attempts have been made to detect molecular oxygen (O_2) absorption bands in the Venus spectrum. In 1921 John and Nicholson (Ref. 1) obtained a series of spectrograms of the solar light reflected by Venus for west and east recessions of Venus from the Sun. Portions of the spectrum containing the α- and B-bands of oxygen (6,300 and 6,900 Å, respectively) were recorded at a linear dispersion of 3 Å/mm. The velocity of Venus relative to the Earth reached the value of 12.8 km/sec which gave a doppler shift $\Delta\lambda$ = 0.27 Å in the 6,300 Å region. As the authors indicated, this doppler shift is adequate for detection of the oxygen absorption band if it is present in the Venus atmosphere in sufficient quantity. However, no signs of the presence of such absorption bands were detected near the telluric oxygen α- and B-bands. Unfortunately, the authors did not indicate the width of the spectrograph slit or other details of the work done in obtaining the Venus spectra.

In 1932 Adams and Dunham (Ref. 2) repeated the study undertaken in Ref. 1, recording the region of the spectrum near 7,600 Å (the oxygen A-band, which is the most intense of the group of bands α, B, and A) with a dispersion of 5.6 Å/mm. The plates were obtained near the eastern elongation of the planet at a

[1]*Izvestiya Krymskoi Astrofizicheskoi Observatorii* (Bulletin of the Crimean Astrophysical Observatory), Vol. XXIX, pp. 3–14, 1963.

relative velocity of 14 km/sec, which gives a doppler shift of 0.37 Å in the region of 8,000 Å. A quantitative study of the spectrograms was not made, but a qualitative investigation of the microphotogram did not disclose any signs of the oxygen absorption lines in the Venus atmosphere. Just as in the previous work, no indication was given of the width of the spectrograph slit or other details.

Finally, in 1959, Heyden, Kiess, and Kiess (Ref. 3), using a linear dispersion of 1.7 – 2.5 Å/mm, also did not detect oxygen absorption bands in the Venus atmosphere, even though the doppler shift was sufficient to separate the bands of the Venus atmosphere from the telluric bands. This study, however, did not indicate the width of the slit for which the spectra were obtained, which oxygen bands were investigated, or the time at which the plates were obtained. From the authors' statements that they did not detect O_2 or H_2O bands in the Venus atmosphere, it can be assumed that they were investigating the oxygen A-band region.

Thus, the spectrographic studies did not detect the oxygen absorption bands in the Venus atmosphere. Reference 1 presented an estimation of the upper limit of the oxygen content in the Venus atmosphere: if oxygen is present then it constitutes less than 0.1% of the content in the Earth's atmosphere.

In considering the question of the spectroscopic detection of oxygen in the Venus atmosphere, it is necessary to take into account several factors. Only the upper portion of the Venus atmosphere above the cloud cover will be considered, where the density is significantly less than in the portion below the clouds. For the Earth, for example, it is known that ¾ of all the atmosphere is found below 10 km and only 25% above 10 km. As a result of this factor, the concentration of the oxygen which we hope to detect will be small and the absorption band must be expected to be weak. If such a weak band is detected, this still will not mean that the quantity of oxygen in the entire Venus atmosphere is small, since we do not have any precise knowledge of the height of the layer of the Venus atmosphere which limits our measurements. Further, not all the telluric oxygen bands are suitable for the purpose of detecting the oxygen in the Venus atmosphere as their absorption coefficients differ sharply. Thus, from the measurements of Allen (Ref. 4), if the absorption coefficient for the α-band is taken as 1, we then have 25 and 350 for the B- and A-bands, respectively. Therefore, the α-bands are very narrow and are often used by astrophysicists to determine the instrumental profile of the solar spectrographs.

The width of the inlet slit of the spectral instrument, its linear dispersion, and the resolving power of the photographic emulsion (graininess) used for photographing the spectrum are of essential importance in the determination of the faint absorption bands (with low equivalent width). With a wide spectrograph inlet slit the individual absorption line becomes wider, its depth diminishes, and the absorption line becomes indistinguishable in the background of the oscillations caused by the graininess of the photographic emulsion. This factor forces us to use particularly precise techniques for the photometric reduction of the photographic plates and to use the narrowest possible spectrograph slits for obtaining the Venus spectra.

II. OBSERVATION CONDITIONS

At the Crimean Astrophysical Observatory of the USSR Academy of Sciences, Venus spectra were obtained during 1961 at a linear dispersion of 1 Å/mm in the red portion of the spectrum, using an echelle-spectrograph installed on the tower solar telescope of this observatory (Ref. 5).

During the east recession of Venus in February 1961, weather conditions were such that only a single plate which was more or less suitable for photometric reduction could be obtained. This spectrum was obtained on a Kodak 103aF plate with an exposure time of 3 hr and a spectrograph inlet slit width corresponding to a segment of 0.17 Å on the spectrum near 6,300 Å. The photographing was initiated when Venus was about 25 deg above the horizon and was continued to a height of about 3 to 5 deg above the horizon.

During the west recession of Venus in August and October of 1961, six spectrograms suitable for photometric reduction were successfully obtained. These were on Kodak 103aE plates with exposures from 1.5 to 2.5 hr, with various spectral widths of the spectrograph slit covering portions of 0.17, 0.12, and 0.08 Å on the spectrum near 6,300 Å. The photographing began with Venus 8 to 10 deg above the horizon and continued until almost sunrise, when Venus was 25 to 30 deg above the horizon. The conditions existing, including the date, the slit width converted to the width $\delta\lambda$ of the spectral interval in the 6,300 Å region of the spectrum, the exposure duration, and also the magnitude of the doppler shift $\Delta\lambda$ corresponding to the relative velocity of Venus are presented in Table 1. The magnitude of the doppler shift was calculated from the change in the geocentric distance of Venus and, for several cases, was measured on the plate by the displacement of the solar metallic lines in the Venus spectrum relative to the telluric oxygen lines. As seen from Table 1, the agreement of the calculated and measured displacements is quite good.

In addition, Sun spectra were obtained at slit widths $\delta\lambda = 0.17$ and 0.08 Å, with the Sun about 15 deg above the horizon, using an exposure time of 0.2 sec on 103aF and 103aE plates.

The plates were developed for 9 min in double strength Ilford Zenith developer at a temperature of 20 – 21°C.

For the photometric processing of the plates, darkening marks were obtained on the 103aF and 103aE plates at the corresponding values of exposure, using the ISP-51 spectrograph with an f = 270-mm camera. The development conditions were the same as those used for the Venus and Sun spectrograms. These darkening marks were used to construct the characteristic curves for the two types of plates and the two exposure times at a wavelength of about 6,300 Å.

Table 1. Prevailing conditions during acquisition of Venus spectra in 1961

Photograph date, 1961	Slit width, $\delta\lambda$, Å	Exposure duration	$\Delta\lambda$, Å		Plate type
			Calculated	Measured	
Feb. 26	0.17	3^h00^m	−0.251	−0.252	103aF
Aug. 16	0.17	1 35	+0.237	- - -	103aE
Aug. 20	0.12	2 10	+0.233	+0.231	103aE
Aug. 22	0.08	2 10	+0.230	+0.233	103aE
Aug. 23	0.08	2 25			103aE
Oct. 20	0.08	1 30			
Oct. 21	0.08	1 30	+0.147	- -	103aE

The lines of the P-branch of the oxygen α-band selected for careful photometric analysis are listed in Table 2. For convenience in reduction, each line was assigned a sequential number. This same table (column 2) presents a complete list of the solar and atmospheric lines located near the selected oxygen lines (wavelength and intensity are given following Rowland). In addition to the lines from Rowland's tables, this list includes the additional water vapor lines observed by Yeropkin and Kondratyev (Ref. 6) for a position of the Sun low above the horizon. The intensities for these lines are enclosed in brackets since we have converted them from the intensity scale used in Ref. 6 to the intensity scale of Rowland's tables; it must be noted that the correspondence of these two scales is not completely satisfactory.

Table 2. Lines of P-branch of oxygen α-band selected for photometric analysis

Line number	O_2, λ, Å	λ, Å	Line source	Intensity	Line number	O_2 λ, Å	λ, Å	Line source	Intensity
		6307,885		−2N			6296,511	V; H_2O	−3
		,558	$O_{16}O_{18}$	−3N			,378		−3
		,07	$O_{16}O_{18}$				,156	Ce^+	−3
		6306,745	$O_{16}O_{18}$	−3	5	6295,966		O_2	3
1	6306,575		O_2	2			6295,818		−3
		6306,414	$O_{16}O_{18}$; H_2O	−3			,657	H_2O	−3N
		,225	$O_{16}O_{18}$; H_2O	−3			,387		−3
		,05	Sc	−3			,29	Ti	
		6305,996			6	6295,186		O_2	3
2	6305,819		O_2	2			6295,039		−3
		6305,674	Sc	−3			6294,672	H_2O	−3N
		,321	H_2O	−2N			,180	H_2O	(−3)
		6304,866		−3N			6293,952		−1
		,578	H_2O	(−3)			,905	H_2O	(0)
		,440	H_2O	(0)			,436	H_2O	(−3)
		,341		−2N			,167		−3
		6303,774	Ti	−2N	7	6292,967		O_2	3
		,496		−2N			6292,827		−2
		6302,955		−3			,622	H_2O	−3N
	6302,771		O_2	2			,369		−3
		6302,508	Fe	5	8	6292,170		O_2	2
		,197	Ce^+	−3			6291,931	H_2O	(−3)
	6302,005		O_2	2			,775	H_2O	(−3)
		6301,852		−3			,062	H_2O	(−3)
		,517	Fe	7			6290,981	Fe	4
		6300,700	Sc^+	−2			,850	H_2O	(−2)
							,547	Fe	−2N
		,331		−2	9	6290,224		O_2	2
		,003	H_2O	(−3)			6289,903	H_2O	−3
		6299,601	H_2O	0			,587		−3
		,421	H_2O	−2	10	6289,403		O_2	1
3	6299,231		O_2	3			6289,181	H_2O	−2
		6298,800	H_2O	(−3)			6288,752		−3
		,650	V	−3			,688	H_2O	(−3)
4	6298,462		O_2	2			,636		−3
		6298,309	H_2O	−3			,554	H_2O	(−3)
		,091	Ti	−3			,327		−2
		6297,808	Fe	5					
		,313		−3					
		,267	H_2O	−3					
		6296,67	Ti	−3 in spot					

III. METHOD OF PHOTOMETRIC PROCESSING OF THE SPECTRA

The processing of the spectra obtained was performed very carefully. The MF-2 nonrecording microphotometer was used to read the intensity (on the microphotometer logarithmic scale) every 0.005 – 0.01 mm of plate displacement as controlled by the micrometer screw. Although this procedure is somewhat laborious, it gives the value of the intensity immediately, and when reading each point the microstage is fixed. The darkening values were converted to intensities by use of the corresponding characteristic curves. The intensity values obtained reflected considerable fluctuations of the plate grain. A smoothing of the intensities was performed using successive averaging over three points in order to somewhat reduce these fluctuations. The intensity curves (registrograms) for the individual groups of lines were then drawn. The lines of the P-branch of the α-band were located in the spectrum as characteristic doublets with distances between them of about 0.8 Å; therefore, the registrogram was constructed for each doublet with the ordinate scale taken to be 100 m/Å. The center was determined for each of the telluric oxygen lines, and the position of the centers was verified by the positions of the lines relative to one another. From these same registrograms, we determined the position of the solar metallic lines in the Venus spectrum relative to the telluric lines. These measurements gave the value of the doppler shift in the Venus spectrum presented in Table 1.

The positions of the solar and the other telluric lines were plotted on the registrograms of the separate telluric oxygen lines in accordance with the data of Table 2 and with consideration for the doppler shift of the solar lines. This eliminated the need for further processing of those groups of oxygen lines where blending of the solar and telluric lines was observed and permitted selection for further processing of the lines without blending. All the selected groups of the oxygen lines were then reduced to a single depth, taken as 1. In this reduction the weaker oxygen lines (e.g., 10, Table 2) and the nearby solar and telluric lines were somewhat intensified. This reduction of all the oxygen lines to a single depth scale was done so as to have the capability of superposing their registrograms on one another and, in this way, to perform an averaging of the photoemulsion grain fluctuation. This method of superposition of a series of lines in the oxygen B-band was used as early as 1934 by Adams and Dunham (Ref. 7) in their work on the detection of oxygen in the atmosphere of Mars.

If, in the Venus spectrum, there is a weak absorption line near each oxygen line at a distance equal to the corresponding doppler shift, then, in such an averaging process, its intensity (more precisely, depth) will not be changed. The solar and telluric lines of the water vapors which are found at differing distances from the Earth's oxygen lines will, in the superposing of the profiles, be distributed in a "random" fashion relative to the center of the averaged profile, and their intensity will be reduced in the ratio of the number of lines used for the averaging. In exactly the same way, the fluctuations of the grain of the plate will be reduced by superposition. Therefore, we may expect that the weak absorption lines caused by the Venus atmosphere will become noticeable on the background of the remaining fluctuations of the plate grain. This technique was used for the processing of all the plates indicated in Table 1, in several cases by two independent observers, and also for the solar spectrum plates.

As indicated above, the individual lines of the P-branch of the oxygen α-band are distributed in pairs with a spacing of 0.8 Å; therefore, by the superposition of individual lines one on the other, it is possible to obtain shoulders of the lines at distances no greater than 0.4 Å from the center of the lines. This distance is quite satisfactory for our purpose since the doppler displacement in the Venus spectrum does not exceed 0.25 Å (Table 1).

IV. DISCUSSION OF RESULTS

Figure 1 presents the average profile for lines 1 – 10 (Table 1) for the spectrum of the Sun. The displacement in Å from the center of the lines is plotted along the ordinate axis. The vertical lines at the top indicate the positions of all the neighboring solar and atmospheric lines (in accordance with Table 2); the solar lines are denoted by the symbol ⊙ and the atmospheric lines by the letter *a*. The following conclusions can be drawn from this averaged profile:

1. The profile obtained is symmetrical to a high degree for the oxygen lines, as it should be, on the basis of the investigations reported (Ref. 4).

2. The oscillations in the shoulder portions of the curve may be caused by an accumulation of weak solar and atmospheric lines; however, these oscillations may also be the result of the averaging of the fluctuations of the photoemulsion grain (e.g., in the left portion of the profile).

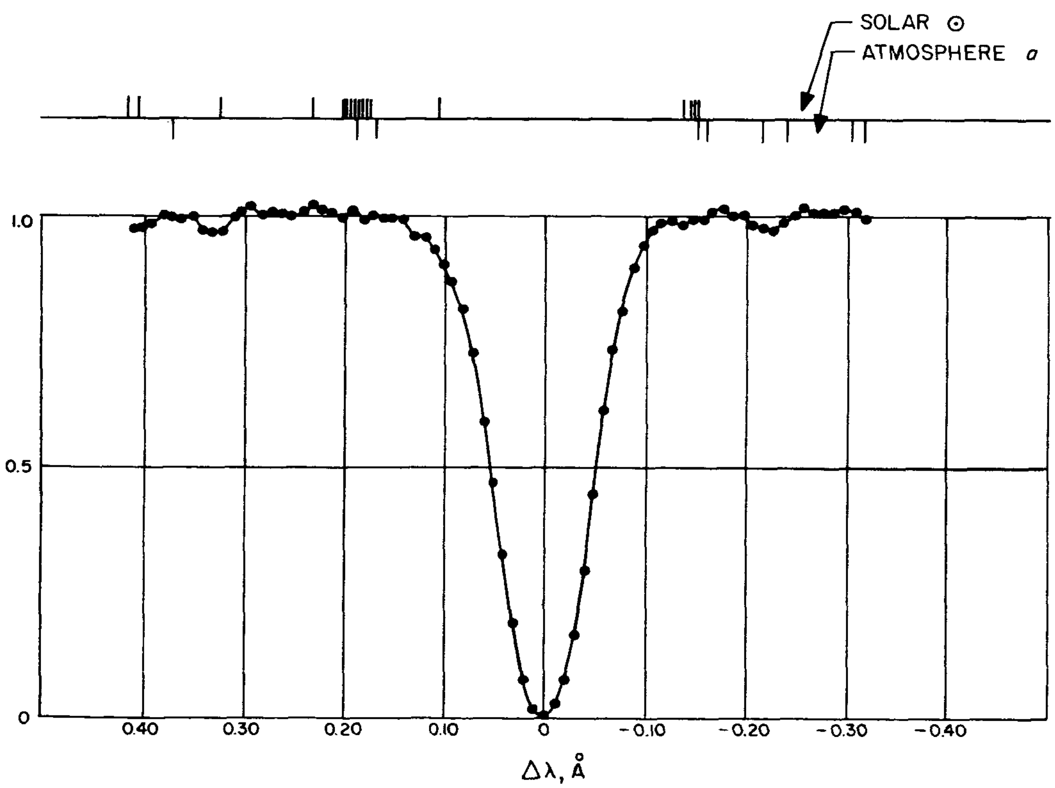

Fig. 1. Averaged profile for ten lines of the telluric oxygen α-band for the solar spectrum

Figure 2 presents the average profile for the lines 1, 2, 4 – 10 (Table 2) in the Venus spectrum. At the top are indicated the positions of the atmospheric (a) and solar ($\odot$) lines, the latter with account for the doppler shift. The averaging was performed with two plates obtained August 22 and 23, 1961. In the center of the profile, just as in the profile of Fig. 1, there are no blending lines and therefore the profile should be symmetrical. The dashed line on the long-wave shoulder of the profile indicates a profile shape symmetrical with the short-wave shoulder. This shows a clearly defined depression on the long-wave shoulder which is represented at the top of the figure in the form of the difference between the two shoulders of the profile. This depression has two minima: one is located at $\Delta\lambda = +0.10$ Å and is caused by the bunching of four weak solar lines near the oxygen lines with the numbers 2, 5, 6, and 7, three of which have an intensity of −3 and one, −2; the second minimum of the depression is located on a portion which is free of blending lines, where there is only a single atmospheric line with $\Delta\lambda = +0.16$ Å located near line 1 and belonging to the oxygen isotope $O_{16}O_{18}$. The concentration of this isotope, from the data of Ref. 6 (VIII) and Ref. 8, amounts to 1/600th of the oxygen present in the atmosphere of the Earth. In addition, this line was reduced in the ratio 1:9, as a result of the averaging, by superposing nine portions of the spectrum in the construction of the profile. Thus this line cannot be responsible for the observed depression. Only one possibility remains: this maximum is located near the shift $\Delta\lambda = +0.23$ Å corresponding to the doppler shift of the Venus spectrum (the position of the shift from Table 1 is shown on Fig. 2 by an arrow) and is caused by a weak oxygen absorption band in the atmosphere of Venus.

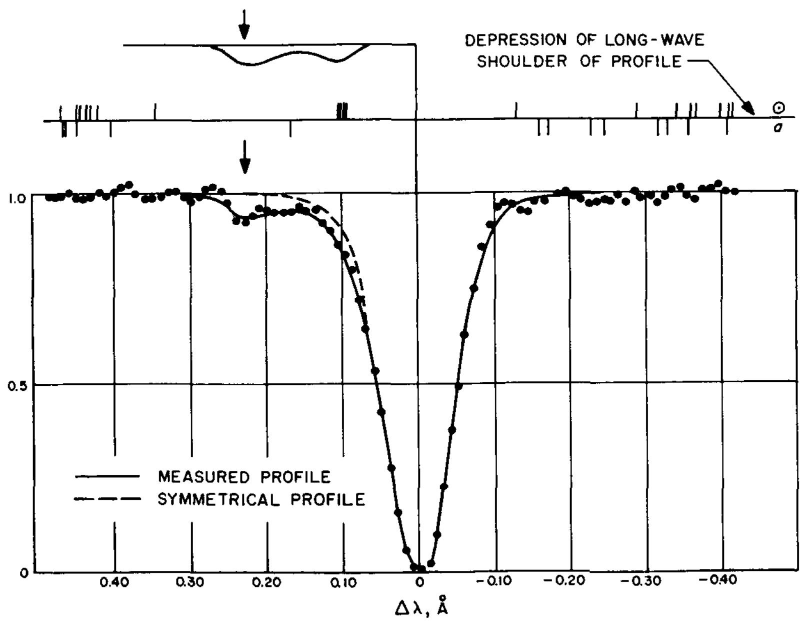

Fig. 2. Averaged profile for nine lines of the telluric oxygen α-band for the Venus spectrum on August 22 and 23, 1961

Figure 3 presents the average profile for the lines 1, 2, 4 – 10 (Table 1) for the Venus spectrum obtained on two plates on October 20 and 21, 1961. Just as in the previous figures, the vertical lines at the top indicate the positions of the atmospheric (a) and the solar (⊙) lines, the latter with consideration for the corresponding doppler shift. In this case, the group of four blending solar lines is located right in the center of the profile. This only deepens the profile somewhat without destroying the symmetry. Therefore, in this case also, it is possible to distinguish a depression of the long-wave shoulder relative to a symmetrical profile shape (dashed line). This depression is shown in the form of the difference of the long-wave and the short-wave shoulders. In the region of the depression there is only a single atmospheric line belonging to an isotope of oxygen. In the discussion of Fig. 2, it was shown that this line cannot be responsible for the depression. There are no other lines that could cause this depression; therefore, only one possibility remains — to ascribe it to the weak oxygen (O_2) absorption line in the atmosphere of Venus, particularly since its position corresponds to the doppler shift $\Delta\lambda = +0.147$ Å, which is marked by an arrow in Fig. 3.

The average profiles of the lines in the Venus spectrum presented in Fig. 2 and 3 were obtained using a spectrograph slit of 0.08 Å.

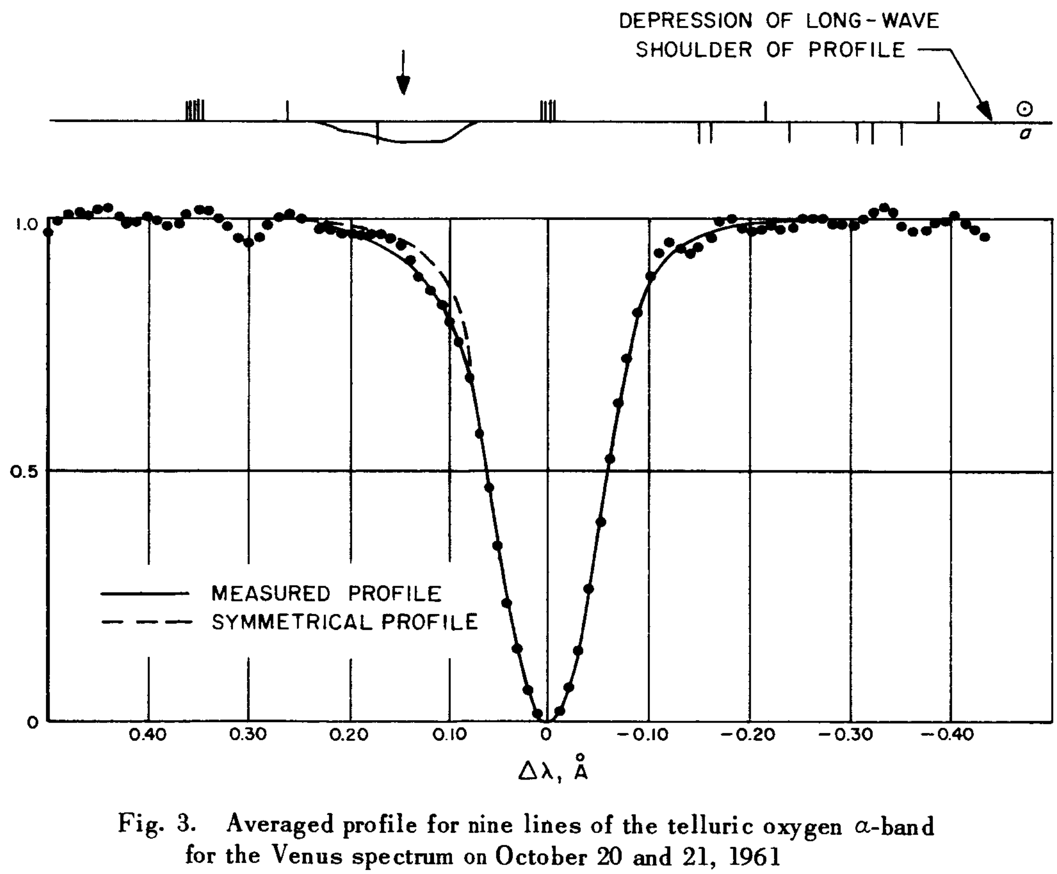

Fig. 3. Averaged profile for nine lines of the telluric oxygen α-band for the Venus spectrum on October 20 and 21, 1961

Figure 4 presents the average profile for the lines 1–4, 6–8 for the Venus spectrum obtained August 20, 1961 using a spectrograph slit of 0.12 Å. As in the preceding figures, the vertical lines at the top indicate the positions of the atmospheric (a) and solar (⊙) lines, the latter positions with consideration for the doppler shift (Table 1). The dashed line shows the symmetrical profile shape while the depression in the form of the difference of the long-wave and short-wave shoulders of the profile is shown separately above. The interpretation of this profile is identical with the interpretation of the profile for the plates of August 22 and 23 (Fig. 2), since the doppler shift lines in the Venus spectrum for August 20, 22, and 23 are practically identical. The left maximum of the depression is to be ascribed to the weak oxygen absorption line in the Venus atmosphere.

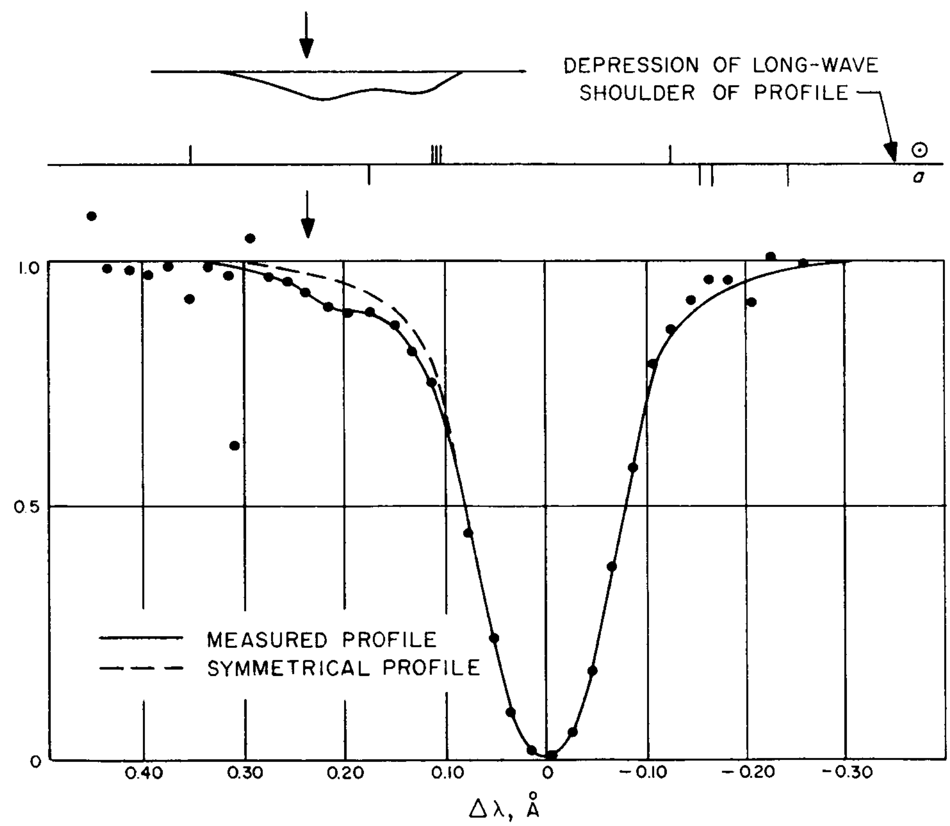

Fig. 4. Averaged profile for seven lines of the telluric oxygen α-band for the Venus spectrum of August 20, 1961

Figure 5 presents the average profile for the lines 1–8 for the Venus spectrum obtained August 16, 1961 using a 0.17 Å slit. As before, the positions of the neighboring atmospheric (a) and solar (⊙) lines, the latter with account for the corresponding doppler shift, are shown at the top. As a result of the large slit width the profile is quite broad, and, moreover, the effect of the graininess of the plate is noticeably stronger than for the preceding profiles. Here again, we notice the depression relative to the symmetrical profile shape caused by a group of solar lines, by a waterline located near line 3, and by the oxygen isotope line. The intensity of the waterline is reduced eightfold in this profile as a result of the averaging over eight portions of the spectrum and cannot be entirely responsible for the depression. The arrow indicates the positions of the oxygen absorption lines of the Venus atmosphere. Thus, once again, the effect of the weak oxygen absorption line of the Venus atmosphere is noted, although the character of the profile is coarser than that in Fig. 2 and 3 obtained with a spectrograph slit only half as wide. The weak absorption of molecular oxygen in the atmosphere of Venus is quite clearly seen in the four profiles considered (Fig. 2–5). This conclusion is confirmed by the absence of blending lines in the corresponding locations of the spectrum, and also by the change in the position of the maximum of the observed depression as a function of the change of the doppler shift in the Venus spectrum.

It is interesting to compare the average profiles considered above with the spectrum obtained on February 26, 1961 when the doppler shift changed from the positive value of August and October (recession of Venus from the Earth) to negative, corresponding to the approach of Venus to the Earth (February 26, 1961). However, the performance of this comparison is hindered by three factors. First, we have available only one spectrum for February 26, in contrast with six for August and October. In addition, as seen from Fig. 1, on the short-wave side of the averaged profile there are located six water bands which can severely interfere with the identification of the depression if it is detected on this side of the profile. Finally, since the spectrum of February 26 was obtained using a wide slit (0.17 Å) the details of the profile become less sharp. However, some comparison can still be made.

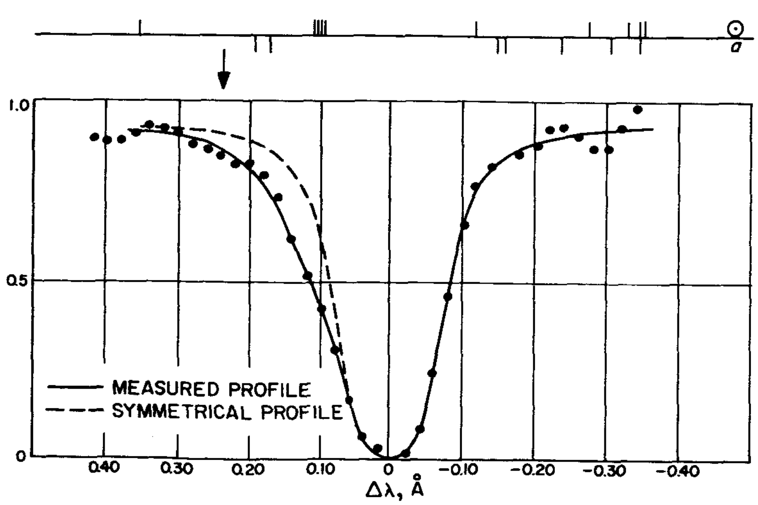

Fig. 5. Averaged profile for eight lines of the telluric oxygen α-band for the Venus spectrum of August 16, 1961

First of all, in the construction of the averaged profile of February 26, all the telluric lines having water vapor blending lines on the short-wave side were eliminated. In this case, only the lines with the numbers 2, 6, and 7 remain. Naturally, the determination of the average profile for three lines will make no large reduction in the effect of the graininess, and the shoulders of the profile will be less clear cut. The comparison is made only with the profile obtained on August 16 using the same slit width. Figure 6 presents the superposition of these two profiles. The profile for February 26 is shown by the solid line. As would be expected, the short-wave shoulder oscillates considerably because of the graininess of the photoemulsion.

At the top are noted the positions of the solar blending lines with consideration for the doppler shift; the first three on the left have an intensity of −3, while the fourth has an intensity of −2N. Even in this profile some dissymmetry can be seen (now, however, located on the short-wave shoulder of the profile); the dashed line shows the superpositioning of the long-wave shoulder on the short-wave. Two depression regions are found: the first, near the peak of the profile, is obviously caused by the three solar lines; the other, on the short-wave shoulder, is caused partially by the fourth solar line with the intensity −2N and by absorption in the atmosphere of Venus, the location of which is shown by the arrow.

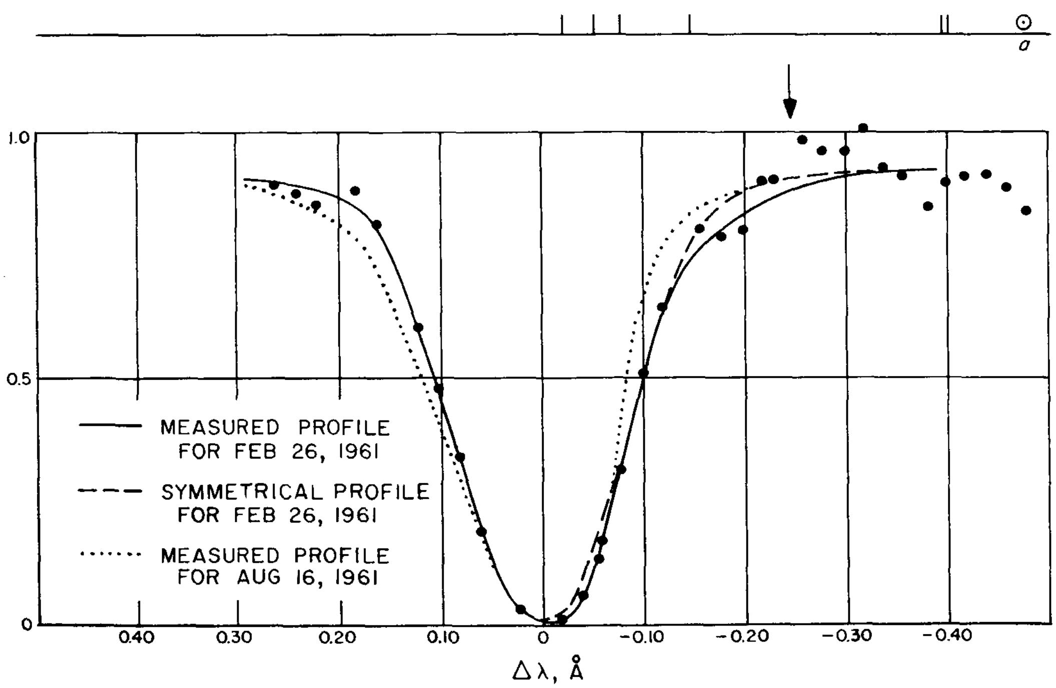

Fig. 6. Averaged profile for three lines of the telluric oxygen α-band for the Venus spectrum of February 26, 1961

In addition, simultaneous consideration of the profiles for February 26 and August 16 (the latter shown dotted) indicates a depression on the long-wave shoulder of the August 16 profile in comparison with the profile for February 26, while the February 26 profile shows a similar depression in the short-wave shoulder. This qualitative comparison tends to confirm that, with the transition from recession of Venus from the Earth (August 16) to approach (February 26), the depression of the profile shifted from the long-wave shoulder to the short-wave. This may serve as confirmation of the conclusion drawn above concerning the presence in the Venus spectrum of a weak absorption band of molecular oxygen O_2 present in the atmosphere of Venus.

Against this conclusion, this objection may be advanced: if there are solar lines located precisely under the telluric oxygen lines, then in the Venus spectrum they would be displaced as a result of the doppler shift, just as the lines corresponding to the gases of the Venus atmosphere. Spectra were obtained of the Sun from the east and west edges using the diffraction spectrograph of the tower solar telescope (Ref. 9) at a linear dispersion of 0.25 Å/mm in the spectrum of fourth order, with a slit width of 0.017 Å. In this case a doppler shift will be noted in the spectrum as the result of the rotation of the Sun; such lines, if they are actually present, can be detected from the dissymmetry of the shoulders of the telluric lines, and this dissymmetry must transfer from one shoulder to the other along with the transition from the east to the west edge of the Sun. A careful investigation of the registrograms of the profiles of all the ten telluric lines used in this study disclosed no noticeable asymmetry of the shoulders. Thus, the objection presented above is considered invalid, and the depressions found may be ascribed to absorption by the molecular oxygen of the Venus atmosphere.

We will still refrain from any quantitative estimate of the oxygen content (in the region of Venus above the cloud layer) responsible for the observed weak absorption band in the Venus spectrum. An extension of this investigation is considered necessary in order to attempt, first of all, to determine, with sufficient reliability, the depression of the profiles on the short-wave shoulder which corresponds to the approach of Venus to the Earth. This is to be our next task.

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